AD-753 162

RADIATION INDUCED F-REGION PLASMA PHENOMENA

Francis W. Perkins, et al

Princeton University

Prepared for:

Advanced Research Projects Agency
Rome Air Development Center

May 1972

RADC-TR-72-263
Technical Report
May 1972

RADIATION INDUCED F-REGION PLASMA PHENOMENA

Princeton University

Sponsored by
Defense Advanced Research Projects Agency
ARPA Order No. 1423

Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

30

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

The Trustees of Princeton University
Princeton, New Jersey 08540

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

Radiation Induced F-Region Plasma Phenomena

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

Francis W. Perkins
Ernest J. Valeo

6. REPORT DATE

May 1972

7a. TOTAL NO OF PAGES

twenty-four ~~(24)~~ 30

7b. NO OF REFS

nine (9)

8a. CONTRACT OR GRANT NO

F 30602-72-C-0053

b. PROJECT NO

c. * Program Code Number 2E20

d. * ARPA Order Number 1423

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

RADC-TR-72-263

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

Monitored by Rome Air Development Center
Griffiss AFB, New York 13440
Attn: OCSE - Mr. F. Wilson

12. SPONSORING MILITARY ACTIVITY

Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, Virginia 22209

13. ABSTRACT

The purpose of the theoretical effort at Princeton is to obtain as complete a theoretical understanding as possible of not only the important physical processes which lead to the experimentally observed effects in the current ionospheric modification program (being undertaken at the Arecibo Observatory and at Boulder, Colorado), but also the scaling laws which predict the results of the future modification experiments (e.g., increased high-frequency modifier power fluxes).

Extensive diagnostics reveal distinct collective phenomena on several scale lengths. Our understanding of short-scale turbulence (wavelengths of 10^{1}-10^{3} cm) allows us to predict quantitatively the level of density fluctuations which can be produced in a controlled manner in the ionosphere. We show that the presence of intense modifier radiation will cause plasma (parametric) instabilities in the ionosphere which result in short-scale turbulence involving plasma waves and ion acoustic waves, and lead to an increased absorption of the modifier power. The density fluctuations associated with the turbulence can scatter radar waves as evidenced by the enhanced signals seen by the Arecibo 430 MHz diagnostics. Our theory has described both the intensity and frequency spectrum of the Arecibo radar scatter diagnostics. The theory provides a good description of the frequency spectrum of the short-scale density fluctuations, especially the plasma line portion.

Our work on long-scale turbulence (wavelengths greater than an ion Larmor radius $\approx$ 10 m) concerns a theory for artificial Spread-F, based on a model of a radiation-induced, self-focussing thermal instability. The predicted growth times are in agreement with the observed formation times (on the order of 1 - 10 seconds) of magnetic field aligned density structures.

DD FORM 1 NOV 65 1473

Ia

UNCLASSIFIED

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ionospheric Modification						
Parametric Instability						
Anomalous Absorption						
Artificial Spread-F						

I b

RADIATION INDUCED F-REGION PLASMA PHENOMENA

Francis W. Perkins
Ernest J. Valeo

Contractor: Princeton University
Contract Number: F30602-72-C-0053
Effective Date of Contract: 26 May 1971
Contract Expiration Date: 26 November 1972
Amount of Contract: $138,405.00
Program Code Number: 2E20

Principal Investigator: Dr. Francis W. Perkins
Phone: 609 452-5641

Project Engineer: Vincent J. Coyne
Phone: 315 330-3107

Contract Engineer: Fred C. Wilson
Phone: 315 330-2478

This research was supported by the Defense Advanced Research Projects Agency of the Department of Defense and was monitored by Fred C. Wilson RADC (OCSE), GAFB NY 13440 under F30602-72-C-0053.

PUBLICATION REVIEW

This technical report has been reviewed and is approved

RADC Project Engineer

RADC Contract Engineer

TABLE OF CONTENTS

ABSTRACT

Collective plasma phenomena induced in the ionospheric F-region by intense high-frequency radiation are examined on several time and length scales. The short wavelengh, high-frequency turbulence associated with the observed high-frequency enhanced electron density fluctuations at the electron plasma frequency is shown to result from parametric excitation of plasma and acoustic waves by the high-frequency radiation. The wave kinetic equation describing the nonlinear evolution of the turbulence is presented. The time asymptotic spectral intensity is calculated and a formula for the total energy absorption from the incident radiation via nonlinear collective effects is obtained. A radiation induced self-focussing instability is found on a length scale somewhat larger than an ion Larmor radius, and is offered as a possible explanation for the occurrence of magnetic field aligned density filaments, which are associated with the phenomenon of "artificial Spread-F." The calculated growth rates are in agreement with the time delay for appearance of spread-F after modifier turn on.

I. SUMMARY

The purpose of the theoretical effort at Princeton is to obtain as complete a theoretical understanding as possible of not only the important physical processes which lead to the experimentally observed effects in the current ionospheric modification program (being undertaken at the Arecibo Observatory and at Boulder, Colorado), but also the scaling laws which predict the results of the future modification experiments (e.g., increased high-frequency modifier power fluxes).

Extensive diagnostics reveal distinct collective phenomena on several scale lengths. The shortest scale phenomena (10^1 - 10^3 cm) are enhanced high-frequency electron plasma oscillations concomittant with an increase in the level of low-frequency (on the order of the ion acoustic frequency) oscillations at the same wavevector. At substantially longer wavelengths (0.1 - 1 km) density striations with wavevectors nearly orthogonal to the geomagnetic field are observed.

Our understanding of short-scale turbulence allows us to predict quantitatively the level of density fluctuations which can be produced in a controlled manner in the ionosphere. The controlled production of short-scale density fluctuations may have important technological applications. Specifically, our work has shown that the presence of intense modifier radiation will cause plasma (parametric) instabilities in the ionosphere. The plasma instabilities result in short-scale turbulence involving plasma waves and an increased absorption of the modifier power. "Parametric instability" means that electromagnetic modifier power spontaneously

converts itself into a combination of electronic plasma waves and acoustic waves. The density fluctuations associated with the plasma waves and acoustic waves can scatter radar waves as evidenced by the enhanced signals seen by the Arecibo 430 MHz diagnostics. Our theory has described both the intensity and frequency spectrum of the Arecibo radar scatter diagnostics. Two principal conclusions are offered: First, a wave-particle scattering process (nonlinear Landau damping) is responsible for the saturation of the parametric instability. This theory provides a good description of the frequency spectrum of the scattered radiation, especially the plasma line portion (radiation scattered with a frequency shift almost equal to the modifier frequency). Second, a comparison of the intensity of the Arecibo scatter diagnostics with theory suggests that the modifier power flux at Arecibo is below threshold for the parametric instability but still large enough to produce enhanced scattering. We recommend that ionospheric modification experiments be changed so that the incident power flux on the ionosphere lies in the 100 - 200 μwatt/m^2 range instead of 50 μwatt/m^2 (Boulder) or 20 μwatt/m^2 (Arecibo). This increase in power flux will assure that short-scale plasma turbulence is fully in the nonlinear range. We have obtained the result for the rate of absorption of the modifier energy due to the excitation of this turbulence and have incorporated this result into the modifier propagation equations to find the total fraction Γ of modifier energy absorbed due to nonlinear processes. This fraction is typically several tenths.

One immediate extension of the results should be to the treatment of more intense modifier fields than is currently possible in order to determine the scaling laws for the turbulence level and absorption rate at very high modifier fluxes.

Our work on long-scale turbulence concerns a theory for artificial Spread-F, based on a model of a radiation-induced, self-focussing thermal instability. The basic idea is simple: A small reduction in plasma density near the reflection point for the modifier radiation leads to focussing of the modifier radiation into the region of reduced density. The more intense radiation then causes increased heating which via pressure gradients further reduces the plasma density. If this model proves to be correct, then the cause of "artificial Spread-F" is quite different from natural Spread-F. The predicted growth times are in agreement with the observed formation times (on the order of 1 - 10 seconds) of magnetic field aligned density structures. These results can profitably be extended to include an analysis of shorter wavelength perturbations than are currently amenable to treatment and of the nonlinear behavior of the instability.

The controlled production of field-aligned plasma density striations allows one to simulate the striations found in natural ionospheric disturbances.

II. INTRODUCTION

The purpose of the theoretical effort at Princeton as supported under ARPA Contract No. F30602-72-C-0053 is to obtain as complete a theoretical understanding as possible of not only the important physical processes which lead to the experimentally observed effects in the current ionospheric modification program (being undertaken at the Arecibo Observatory and at Boulder, Colorado), but also the scaling laws which predict the results of the future modification experiments (e.g., increased high-frequency modifier power fluxes).

In the modification experiments, powerful high-frequency radio transmitters of frequency up to the F region cutoff frequency f_2 are beamed at the upper ionosphere. These transmissions are sufficiently strong and well-collimated that even if only a moderate fraction of the incident energy were to be absorbed, the energy balance of the F region would be significantly changed. A review of the experimental configuration at Boulder and many of the results are available in a paper by Utlaut and Cohen.[1]

Extensive diagnostics reveal distinct collective phenomena on several scale lengths. The shortest scale phenomena are enhanced high-frequency electron plasma oscillations concomittant with an increase in the level of low-frequency (on the order of the ion acoustic frequency) oscillations at the same wavevector. At substantially longer wavelengths, comparable to the ion Larmor radius r_{Li} (about 5 m), and lower frequencies (typical times for variation are from 1 - 10 seconds), density disturbances with wavevectors nearly orthogonal to the geomagnetic field are observed.

In the regime of short-scale turbulence, our work has shown[2] that the presence of intense modifier radiation will cause plasma (parametric) instabilities in the ionosphere. The plasma instabilities result in short-scale turbulence involving plasma waves and an increased absorption of the modifier power. "Parametric instability" means that electromagnetic modifier power spontaneously converts itself into a combination of electronic plasma waves and acoustic waves. The density fluctuations associated with the plasma waves and acoustic waves can scatter radar waves as evidenced by the enhanced signals seen by the Arecibo 430 MHz diagnostics. Our theory has described both the intensity and frequency spectrum of the Arecibo radar scatter diagnostics. Two principal conclusions are offered: First, a wave-particle scattering process (nonlinear Landau damping) is responsible for the saturation of the parametric instability. This theory provides a good description of the frequency spectrum of the scattered radiation, especially the plasma line portion (radiation scattered with a frequency shift almost equal to the modifier frequency). Second, a comparison of the intensity of the Arecibo scatter diagnostics with theory suggests that the modifier power flux at Arecibo is still below threshold for the parametric instability. We recommend that ionospheric modification experiments be changed so that the incident power flux on the ionosphere lies in the 100 - 200 μwatt/m^2 range instead of 50 μwatt/m^2 (Boulder), or

20 μwatt/m^2 (Arecibo). This increase in power flux will assure that short-scale plasma turbulence is fully in the nonlinear range.

Our work on long-scale turbulence concerns a theory for artificial Spread-F, based on a model of a radiation-induced, self-focusing thermal instability. The basic idea is simple: A small reduction in plasma density near the reflection point for the modifier radiation leads to focusing of the modifier radiation into the region of reduced density. The more intense radiation then causes increased heating which via pressure gradients further reduces the plasma density.

Let us now examine in greater detail the status of our understanding of collective phenomena on the various scale lengths.

III. SHORT-SCALE TURBULENCE

The appearance of a large enhancement of electron density fluctuations of large wavevector k, comparable with an inverse Debye length λ_D (approximately 1 cm for f_2 parameters), i.e., $k\lambda_D \lesssim 1$, and of frequency close to the modifier frequency suggests that collective plasma wave phenomena are playing an important role in the experimental dynamics.

At first noted by Perkins and Kaw,[2] the energy density delivered by the Boulder transmitter to the F region at heights near the cutoff exceeds the threshold for the excitation of a parametric instability in which high-frequency electron plasma waves and low-frequency ion acoustic waves are excited simultaneously. These instabilities result from the decay of the modifier (parametric pump) field into collective modes of plasma oscillation at a rate faster than energy is dissipated from them resulting in growth of these modes. The wavevector and frequency sum rules

$$\underset{\sim}{k}_o = \underset{\sim}{k}_p + \underset{\sim}{k}_{ia} ,$$

$$\omega_o = \omega_p \pm \omega_{ia} ,$$

corresponding to momentum and energy conservation respectively, must be nearly obeyed if the time averaged energy flow is to be nonzero. Here the subscripts refer to the pump (o), electron plasma (p), and ion acoustic waves (ia), respectively. If the plus sign is taken in the above formulae, yielding a plasma wave of frequency smaller in magnitude than the pump frequency, then the direction of energy flow is from the modifier <u>into</u> the plasma. The opposite is true for the choice of minus sign. We see then that any enhanced level of plasma waves due to this process will have a frequency less than that of the modifier. Neglecting dissipation and the geomagnetic field for simplicity, the pump wave satisfies the dispersion relation

$$\omega_o^2 = \omega_{pe}^2 + k_o^2 c^2 \quad ,$$

at each point in space. The logitudinal plasma waves satisfy the dispersion relation

$$\omega_p^2 = \omega_{pe}^2 [1 + 3(k_p \lambda_D)^2] \quad ,$$

where ω_{pe} is the electron plasma frequency, and the ion acoustic waves satisfy the relation

$$\omega_{ia} = (k\lambda_D)\omega_{pi}(1 + 3T_i/T_e)^{1/2} \quad ,$$

with ω_{pi} the ion plasma frequency, and $T_e(T_i)$ the electron (ion) temperature. Since $\omega_p >> \omega_{ia}$, if the sum rules are to be satisfied, we must have $\omega_o \simeq \omega_p$, i.e., the instability occurs where the plasma density is near the cutoff density.

This instability has been invoked as the cause of the enhanced fluctuation levels observed via the backscatter diagnostics at Boulder. The linear theory[3] of this instability in which one derives the threshold (minimum) level of the pump field necessary for growth of, and the growth rate and frequency of, infinitesimal perturbations is well known. In order to apply a theory of parametric instabilities to the interpretation of the observed fluctuation level the linear theory must be supplemented by a nonlinear theory which takes account of the finite amplitude of the excited waves and the interactions between them if the final level of turbulence is to be found. The formulation of equations describing the nonlinear evolution of the plasma wave turbulence and the solution of these equations to determine the nonlinear level of the spectral intensity of electron density fluctuations, I_k, has constituted one of the major activities at Princeton.

In order to make progress in this effort, several simplifying assumptions were made in the formulation of a model. The principal ones and their justification are as follows:

1. The wave vector of the pump is taken as zero. The dipole approximation is a good one because the typical wavevectors of the electrostatic plasma waves are larger in the ratio c/v_{Te} (greater than 10^3 for the F region) where c is the speed of light, and v_{Te} is the electron thermal velocity. Thus, the wavevector of the pump may be neglected in comparison.

2. The plasma is assumed homogeneous. The typical wavelengths of plasma turbulence, on the order of 10^1-$10^2\lambda_D$ ($\lambda_D \approx 1$ cm) are small compared to the density gradient scalelength L (10^2 km) and this makes the assumption plausible. Indeed, Perkins and Flick[4]

have demonstrated that the linear theory of a homogeneous plasma is directly applicable to such a mildly inhomogeneous plasma as the F region. We return to the question of the effects of the plasma inhomogeneity after a discussion of the results of the non-linear theory.

3. The pump amplitude is sufficiently small so that the maximum growth rate of the unstable waves, $\gamma_M = (\omega_{pe}/16)(E_o^2/4\pi nT)$, does not exceed the ion acoustic frequency, i.e., $\gamma_M \leq \omega_{ia}$. Here $E_o^2/4\pi$ is the pump energy density, and nT is the plasma particle kinetic energy density. For such small pump intensities, the weak turbulence theory[5] of plasma has been shown to be applicable.[6]

4. The electron and ion temperatures are comparable ($T_e \approx T_i$). This assumption (well satisfied in the ionosphere) guarantees a large damping decrement for the low-frequency oscillations (comparable with their oscillation frequency) and makes possible an explicit solution for these fluctuations in terms of the high-frequency plasma wave turbulence. The problem then reduces to the simpler one of describing the evolution of only the plasma wave turbulence.

Under these conditions we have shown that the electron plasma wave spectral intensity $I_{\underset{\sim}{k}}$ [the electric field energy density/volume/$(\Delta k)^3$] satisfies a kinetic equation of the form

$$\frac{1}{2}\, dI_{\underset{\sim}{k}}/dt = I_{\underset{\sim}{k}}\left[\gamma_{\underset{\sim}{k}} - \nu_e + \int d\underset{\sim}{k}'\, M(\underset{\sim}{k}, \underset{\sim}{k}')\, I_{\underset{\sim}{k}'}\right] + S_{\underset{\sim}{k}} \quad . \tag{1}$$

Here $\gamma_{\mathbf{k}}$ is the linear growth rate due to the presence of the pump, ν_e is the damping decrement of plasma waves, $M(\mathbf{k}, \mathbf{k}')$ is the matrix element which describes the nonlinear interaction, and $S_{\mathbf{k}}$ is the source term which represents the rate of spontaneous emission of plasma waves.

Substantial progress has been made in the solution of Eq. (1). In general, $I_{\mathbf{k}}$ is a function of three wavevector components k_j, but an examination of the symmetry properties of Eq. (1) shows that axisymmetry of $I_{\mathbf{k}}$ about the direction of $\mathbf{E}_o$ is preserved in time. We have restricted ourselves to a consideration of such a class of solutions making the problem a two-dimensional one. With the use of an approximate form of the matrix element which, however, preserves the symmetry properties and magnitude of M, we have obtained[7] an analytic solution to this equation in two dimensions. We have also analyzed Eq. (1) retaining the exact form of M, and taking the spectral intensity as one-dimensional with its wavevector collinear with the pump field direction. In this case we have solved[8] Eq. (1) numerically and also analytically for the time asymptotic solution in the limit in which the small source term is neglected. The results for the total wave energy and nonlinear absorption coefficient are in excellent agreement for the last two analyses, and a factor of three larger than that obtained for the analysis using an approximate form for M. We present the results of the analysis obtained by using the exact form of M below as the details of the shape of the spectral intensity are more accurately obtained in this case. The results are as follows:

1. When the pump field is switched on, the plasma wave energy first increases exponentially with a growth rate equal to γ_M. The total wave energy reaches a greatly enhanced level and oscillates about a mean value with an analytically predictable frequency. These oscillations decay in time as predicted by several theorems which we have proven regarding the general behavior of any solution of the kinetic equation and which demonstrates that a steady state can be realized. This behavior is shown in Fig. 1, where the total plasma wave energy is plotted versus time for a pump intensity about four times the threshold intensity.

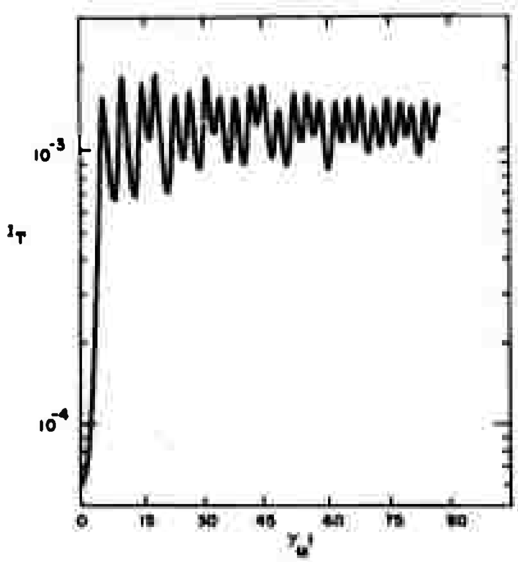

Fig. 1. The evolution of the total plasma wave energy density. $I_T = \sum_k E_k^2/4\pi nT$, and γ_M is the maximum value of the linear growth rate. (722113)

2. Figure 2 shows the time-averaged mode spectrum for the sample case of Fig. 1. The general characteristics are a distinct narrow spike near the linearly most unstable mode driven by the external pump field, followed by a distinctly separated spectrum of waves which have been secondarily driven unstable. In contrast, the analytic solutions obtained with an approximate form of the matrix element have shown a smooth spectrum of plasma waves with

only a single maximum. The primarily driven waves are separated in frequency from the pump by $\sim\omega_{ia}$ whereas the minimum separation from the pump frequency of the secondarily driven waves is $\sim 3\omega_{ia}$. The width in frequency (and wavevector) of the enhanced spectral intensity increases linearly with pump intensity.

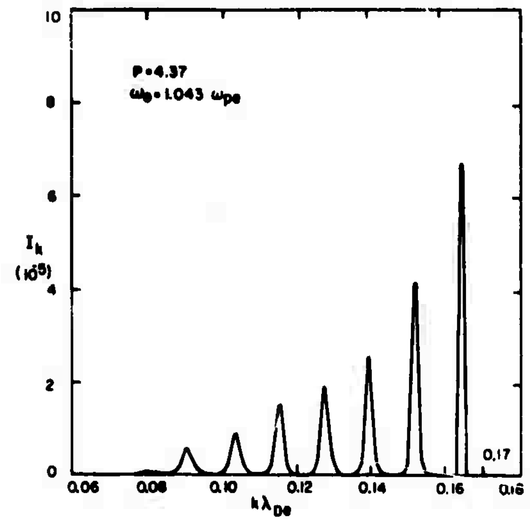

Fig. 2. The time-averaged spectral intensity, I_k, of plasma waves versus wave number. I_k is normalized to the plasma kinetic energy density. If the pump were a plasma wave of frequency ω_o, its wavevector would be $k_o = 0.17\lambda_D^{-1}$. (722115)

3. The total wave energy increases as the square of the pump field intensity according to the formula

$$I_T = 6.24(E_o/E_T)^4 \nu_e/\omega_{pe} \quad ,$$

where the threshold electric field is

$$E_T^2/4\pi nT = 16(\nu_e/\omega_{pe}) \ .$$

Here I_T is the total plasma wave electric field energy density normalized to the particle energy density

$$I_T = \sum_k (|E_k|^2/4\pi nT) \quad .$$

This result has been obtained both from the numerical analysis, as is shown in Fig. 1, and from the analytic analysis.

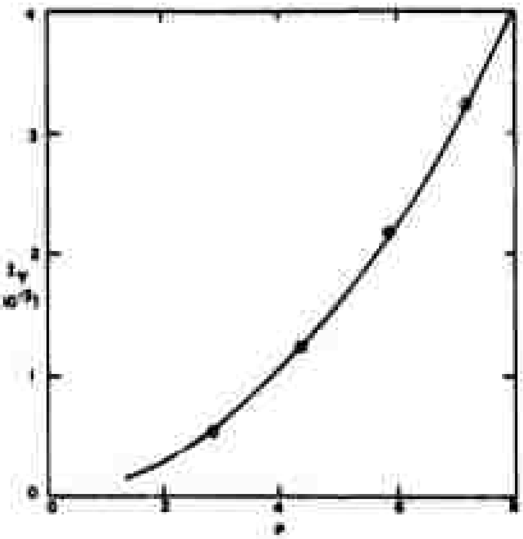

Fig. 3. The time-averaged energy density in the self-consistent plasma waves versus the pump field intensity, $I_T = \sum_k E_k^2/4\pi nT$ and $P = E_o^2/E_T^2$. The solid line is the curve $I_T = 6.24P^2\nu_e/\omega_{pe}$. (722112)

4. The effective absorption rate of the pump ν^* increases linearly with the pump field intensity according to the formula

$$\nu^* = \nu_e (E_o/E_T)^2 \quad . \tag{2}$$

5. The result for the local value of the nonlinear absorption rate may be incorporated into the propagation equation for the electromagnetic wave in order to determine the fraction of incident energy absorbed by nonlinear processes. We have done this analysis using the geometric optics (WKB) approximation for the propagation of the modifier, assuming a horizontally stratified ionosphere and a pump frequency less than f_2. The result (valid for $\Gamma < 1$) is

$$\Gamma = (F_o/F^*) \ \ln \ [\tfrac{1}{4}(H\omega_o/c)^{2/3}]$$

where $F_o = E_v^2 c/8\pi$ = r.m.s. power flux incident on the ionosphere, and $F^* = nTc(c/H\omega_o)$. Here H is the density gradient scale length and E_v^2 is the vacuum value of the modifier intensity. Taking the following typical values for the F region:

$$n = 4\cdot 10^5 \text{ cm}^{-3} \ ,$$
$$T = 0.1 \text{ eV} \ ,$$
$$H = 10^7 \text{ cm} \ ,$$
$$\omega_o = 3\cdot 10^7/\text{sec} \ ,$$

we obtain $\Gamma \simeq 0.5$ for the fraction of the incident energy absorbed by nonlinear processes.

6. The question of the angular dependence of the spectral intensity has been resolved in part. The prediction of the two-dimensional treatment using an approximate form of the matrix element is that the spectral intensity is very sharply peaked along the direction of the modifier electric field. It is expected that a small amount of inhomogeneity can significantly alter these results. We have done preliminary work along these lines and have found that the extension of the analysis to include a mildly inhomogeneous plasma results in a spectral intensity with an angular half-width on the order of 30°. Further work remains to be done along these lines.

There are several areas in which further research is desirable at this point. One is to examine in more detail the angular dependence of the spectral intensity. Another is to extend the nonlinear theory to include more intense modifier fields, i.e., to those which give rise to linear growth rates somewhat greater than the ion acoustic frequency. A third area for future research is the inclusion of the magnetic field in the propagation equations for the modifier and plasma waves.

IV. LONG SCALE TURBULENCE

We have offered a possible explanation of the formation of magnetic field aligned density irregularities, "artificial Spread-F," as due to self-focussing of the pump field into filaments of varying intensity creating corresponding density filaments. We have formulated a model which demonstrates the physical processes involved but which does not treat the complex ray trajectories present in the experiments. The principal results, those for the growth rates of such field-aligned irregularities, are in reasonable agreement with the observed time scale for density variation on these long-length scales.

The mechanism which leads to instability may be seen from the following simple picture: In the unperturbed state, there is no horizontal variation and the electromagnetic flux reaching the critical height is independent of position. If we perturb this state by heating alternate flux tubes, then the density in these tubes at the critical height decreases because of plasma expansion. The radiation is refracted into these less dense tubes from the adjacent ones, causing further heating through increased absorption. This is the basic "feedback mechanism" which causes the instability. The picture is slightly complicated by the fact that, although the density near the critical height is reduced causing ray convergence, the density further down the flux tube increases due to an influx of particles from greater heights. These two effects compete in determining the net refraction of the ray and only if the first dominates is there instability.

The assumptions which go into the model are as follows:

1. The ionosphere is assumed horizontally stratified and the ambient magnetic field vertical (in the $\hat{z}$ direction).

2. The times of interest are assumed sufficiently small and the variation perpendicular to the magnetic field sufficiently gentle so that the plasma motion across the field may be neglected.

3. The modifier radiation is assumed vertically incident and totally absorbed at the critical density due to the short-scale turbulence described above.

4. The energy in the modifier is assumed to be preferentially delivered to high energy electrons (those in the tail of the velocity distribution) which are ineffective in transferring their energy to the bulk plasma until they have traversed a mean free path. The model accounts for this by assuming absorption of all the incident modifier energy flux at the critical height and treating this absorbed energy as a distributed source in the electron energy equation. Since ion neutral collisions are relatively frequent at f_2 heights ($\nu_{in} \sim 1$/sec), the ion and neutral temperatures are identical. Because the dominant energy loss mechanism available to the electrons, collision with the ions, is slower $[\nu_{ei}(m_e/m_i) << \nu_{in}]$ the electron energy equation must be solved.

5. The electromagnetic field is assumed to propagate in the geometric optics approximation. This approximation limits our treatment of perpendicular wavelengths to those for which diffraction effects are negligible. This approximation is the first to break down as the transverse wavelength of the irregularity decreases.

6. Since the electron cyclotron frequency is much less than the electron plasma frequency, the magnetic field is neglected in the ray equations.

The growth rate γ was studied as a function of three parameters: the perpendicular wavevector of the perturbation p, the effective mean free path of the heated electrons λ_{mfp}, and the shape of the density profile. The latter variation was achieved by choosing a parabolic density profile below the critical height Z_{cr} of the form

$$\frac{n}{n_{cr}} = \frac{Z}{Z_{cr}} \frac{[1 - a(Z/Z_{cr})]}{(1 - a)} ,$$

for $Z \leq Z_{cr}$. Here n_{cr} is the critical density. The values $a = 0$ and $a = 0.5$ correspond respectively to a linear profile and to absorption at maximum density. This profile is matched along with its first derivative at the critical height to a profile of the form

$$n \propto (b_1 + b_2 Z) \exp(-Z/L)$$

for $Z \geq Z_{cr}$, where $L = 2T/m_i g$ is the barometric scale height. The density profile is varied by changing a, keeping Z_{cr} fixed at $0.6L$. The other important parameters, the electron-ion and ion-neutral collision frequencies are assumed to vary with temperature and density as follows:

$$\nu_{ei} = \frac{\nu^{o}_{ei}(n/N)}{(T/T_o)^{3/2}} \quad ,$$

$$\nu_{in} = \nu^{o}_{in} \exp(-2Z/L) \quad ,$$

where N is the peak density and T_o the ambient temperature. The predominant neutral is assumed to be atomic oxygen. The values of $\nu^{o}_{ei} = 300/\mathrm{sec}$ and $\nu^{o}_{in} = 4/\mathrm{sec}$ are chosen as typical.

The results of the analysis are most conveniently given in graphical form and are shown in Fig. 4 where the growth rate is plotted vertically versus the perpendicular wavevector of the perturbation. The growth rate is normalized to the thermal diffusion time NL^2/R with $R = 3.16(NT_o/m_e)\nu^{o}_{ei}$ the electron thermal conductivity in the Z direction.[9] The modifier energy density is denoted by I_o and g denotes the gravitational acceleration. For reference, under typical conditions a value of 1 for $\bar{\gamma}$ corresponds to a growth rate of $\gamma \approx 10^{-2}/\mathrm{sec}$, and the dimensionless factor $\{[(\nu^{o}_{ei})^2 c/\nu^{o}_{in} g][m_e^2/m_i^2]\}$ in the definition of $\bar{p}$ typically equals 10^3.

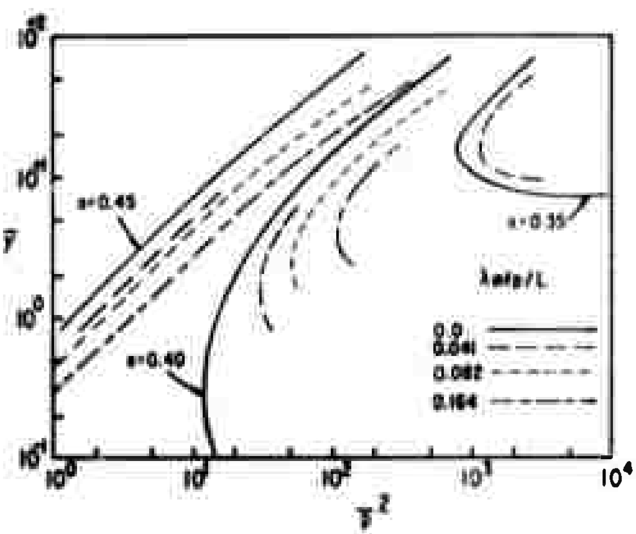

Fig. 4. Plot of the growth rate $\bar{\gamma}$ versus perpendicular wavevector of the perturbation $\bar{p}$, both in dimensionless units, for several values of the heated electron mean free path λ_{mfp}, and the curvature a of the underside density profile. 722121)

Problems for future study include extension of the analysis to perpendicular wavelengths comparable with the ion Larmor radius, and formulation of estimates for final level of turbulence due to nonlinear effects.

V. CONCLUSION

Our examination of plasma phenomena on both short and long length scales has allowed us to obtain an understanding of many aspects of the plasma physics of the modification program. We have developed a quantitative description of the nonlinear development of the short-scale turbulence driven by the modifier near the cutoff height. Using this description, we have calculated the total modifier energy absorbed by nonlinear processes. The observed field aligned density structures with wavelenghts perpendicular to the magnetic field greater than an ion Larmor radius may result from a self-focussing thermal instability induced by the modifier. We have analyzed the linear theory of this instability and have obtained growth rates in agreement with the observed formation time of these irregularities. Further work on the nonlinear evolution of this instability is needed. Additional work is also needed on the development of a description of plasma behavior in the intermediate scale length regime where wavelengths perpendicular to the magnetic field are comparable to an ion Larmor radius.

VI. REFERENCES

[1] W. F. Utlant and R. Cohen, Science 174, 245 (1971).

[2] F. W. Perkins and P. K. Kaw, J. Geophys. Res. 76, 282 (1971).

[3] V. P. Silin, Zh. Eksp. Teor. Fiz. 48, 1679 (1965); [Sov. Phys.-JETP 21, 1127 (1965)]; D. F. Du Bois and M. V. Goldman, Phys. Rev. Letters 14, 544 (1965); K. Nishikawa, J. Phys. Soc. Japan 24, 916, 1152 (1968); J. R. Sanmartin, Phys. Fluids 13, 1533 (1970).

[4] F. W. Perkins, and J. Flick, Phys. Fluids 14, 2012 (1971).

[5] R. Z. Sagdeev and A. A. Galeev, in Nonlinear Plasma Theory (W. A. Benjamin, Inc., New York, 1969), p. 89.

[6] E. J. Valeo, Interaction of High Frequency Electric Fields with Plasma, Ph.D. Thesis, Princeton University (1971).

[7] E. Valeo, C. Oberman, and F. W. Perkins, Phys. Rev. Letters 28, 340 (1972); similar results have been obtained by D. F. Du Bois and M. V. Goldman, Phys. Rev. Letters 28, 218 (1972).

[8] W. L. Kruer and E. J. Valeo, Princeton University MATT-919 (1972).

[9] S. I. Braginskii, in Review of Plasma Physics (Consultants Bureau, New York, 1965), Vol. I, p. 217.